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Can the 33 s pulsations observed from AE Aquarii be explained in terms of accretion onto the white dwarf surface ?

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Abstract. The 33 s pulsing component observed from AE Aqr is frequently assumed to be the result of accretion onto the surface of a rotating white dwarf. The validity of this assumption is discussed in the present paper. I show that under the conditions of interest the white dwarf is in the state of *supersonic propeller* and the efficiency of plasma penetration into its magnetosphere is $\lesssim 0.1\%$. This is too small to explain the observed luminosity of the pulsing component. Moreover, I find that for the currently established value of the angle between the magnetic and rotational axes of the white dwarf, the material entering the magnetosphere at the boundary can never reach its surface by flowing along the magnetic field lines. I conclude that the assumption about the direct accretion onto the surface of the white dwarf in AE Aqr contradicts the observational data obtained in the optical/UV and thus cannot be accepted.

Key words. accretion – binaries: close – stars: magnetic fields – stars: white dwarfs – stars: individual: AE Aqr

1. Introduction

AE Aquarii is a non-eclipsing close binary system with an orbital period $P_{\rm orb} \approx 9.88$ hr and orbital eccentricity $e \approx 0.02$. It is situated at the distance of $\sim (100 \pm 30)$ pc. The normal component (secondary) is a K3-K5 main sequence red dwarf. The primary is a magnetized white dwarf rotating with a period of 33 s. The inclination angle of the system is limited to $50^{\circ} < i < 70^{\circ}$ and the mass ratio is $q = M_2/M_1 = 0.77 \pm 0.03$ (for references see Table 1 in Ikhsanov 2000).

AE Aqr emits detectable radiation in almost all parts of the spectrum. It was observed as a powerful non-thermal flaring source in the radio (Bastian et al. 1988) and gamma-rays (Bowden et al. 1992; Meintjes et al. 1994). The optical, UV and X-ray radiation of the system is predominantly thermal and is coming from at least three different sources. The visual light is dominated (up to 95%) by the secondary (Bruch 1991; Welsh et al. 1995). The contribution of the primary is observed mainly in the form of 33 s (and 16.5 s) coherent oscillations detectable in the optical, UV and X-rays (Patterson 1979; Patterson et al. 1980). Study of the optical-UV spectrum and profiles of the pulsations (Eracleous et al. 1994) has shown that the pulsing radiation is coming from two hot ($T \simeq 26000$ K) spots with a projected area of $\sim 4\,10^{16}$ cm^2, which are situated on the white dwarf surface. Placing these spots at the magnetic pole regions of the primary, Eracleous et al. (1994) have estimated the value of the angle between the rotational and magnetic axes of the white dwarf to be $75^{\circ} \lesssim \beta \lesssim 77^{\circ}$. The remaining light comes from a highly variable extended source which manifests itself in the blue/UV continuum, the optical/UV broad single-peaked emission lines and the non-pulsing X-ray component. This source is spread around the magnetosphere of the primary and is associated with the mass-exchange process in the system (for a detailed system description see Eracleous & Horne 1996 and Ikhsanov 2000).

On the grounds of the properties observed in the optical, AE Aqr was classified as a nova-like star belonging to the DQ Herculis subclass of magnetic cataclysmic variables. Following this notion, it has been suggested that the primary is a magnetized accretion-powered white dwarf undergoing disk accretion (Patterson 1979). Correspondingly, the flaring activity of the system was interpreted in terms of a variable mass accretion rate onto the primary surface (van Paradijs et al. 1989).

However extensive investigations of the system over the last five years have clearly shown that AE Aqr does not fit this model. First, studies of the 33 s pulsations in the optical/UV (Eracleous et al. 1994) and X-rays (Reinsch et al. 1995; Clayton & Osborne 1995; Choi et al. 1999) have

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shown no correlation between their amplitudes and the flaring of the system. This allowed Eracleous et al. (1994) to conclude that flares are not related to the process of depositing material onto the primary surface. Second, analysis of the Hα Doppler tomogram of AE Aqr has shown no evidence of a developed Keplerian accretion disk in the system. Instead, it has shown that the material inflowing through the L1 point into the Roche lobe of the primary is then streaming out from the system with an average velocity $\sim 300\,\mathrm{km\,s^{-1}}$ (Wynn et al. 1997; Welsh et al. 1998). Finally, de Jager et al. (1994) have reported the mean spindown rate of the white dwarf $\dot{P}_\mathrm{s} = 5.64\times10^{-14}\,\mathrm{s\,s^{-1}}$ which implies the spindown power of $L_\mathrm{sd} = I\Omega\dot{\Omega} \sim 10^{34}\,\mathrm{erg\,s^{-1}}$. L_sd exceeds the observed UV and X-ray luminosities of the system by a factor of 120 and its bolometric luminosity by a factor of more than five[1]. This indicates that the spindown power dominates the energy budget of the system and raises the question of the nature of the spindown torque, which would appear to be much larger than any inferred accretion torque.

Four alternative answers to this question and, correspondingly, four alternative theoretical models of the system are currently under discussion: (i) the magnetic propeller model (Wynn et al. 1997), (ii) the spin-powered white dwarf pulsar model (Ikhsanov 1998), (iii) the gravitational wave emitter model (Choi & Yi 2000) and (iv) the differentially rotating white dwarf model (Geroyannis 2001). Though these models essentially differ from each other in many aspects they have an important common point. Namely, the mass-exchange picture in AE Aqr is interpreted in terms of the propeller action by the white dwarf. This implies that the magnetic field of the white dwarf is strong enough for the magnetospheric radius,

$$R_\mathrm{m} = \eta \left(\frac{\mu^2}{\dot{M}\sqrt{2GM_1}} \right)^{2/7}, \tag{1}$$

to be larger than its corotational radius,

$$R_\mathrm{cor} = 1.4\,10^9\ M_{0.8}^{1/3}\ P_{33}^{2/3}\ \mathrm{cm}. \tag{2}$$

Here μ, $M_{0.8} = M_1/0.8M_\odot$ and $P_{33} = P_\mathrm{s}/33\,\mathrm{s}$ are the magnetic dipole moment, the mass and the spin period of the white dwarf, respectively. $\dot{M}$ is the mass accretion rate onto the primary magnetosphere and $0.5 \lesssim \eta \lesssim 1$ is the parameter which accounts for the geometry of the accretion flow. Under these conditions the white dwarf is in the *centrifugal inhibition regime* and is able to eject the material out of the system due to the propeller action.

One of the important questions, which remains to be explained within this approach, is the origin of the hot spots on the white dwarf surface. According to the canonical propeller model (e.g. Davies et al. 1979) no accretion occurs onto the surface of a star in the state of propeller. This indicates that the direct accretion onto the surface of the white dwarf in AE Aqr cannot be responsible for the origin of the hot polar caps and hence an alternative mechanism should be invoked. Following this conclusion, it has been suggested that the polar caps are heated due to dissipation of the magnetic or/and rotational energy of the primary. In particular, due to the dissipation of Alfvén waves (Wynn et al. 1997) or/and due to the impact of the backflowing relativistic particles accelerated in the magnetosphere of the white dwarf (Ikhsanov 1998).

A different possibility to interpret the hot polar caps phenomenon has been discussed by Kuijpers et al. (1997), Meintjes & de Jager (2000) and Choi & Yi (2000). These authors pointed out that the mass accretion rate onto the white dwarf surface required to explain the observed luminosity of the pulsing component is $\dot{M}_\mathrm{a} \lesssim 10^{14}\,\mathrm{g\,s^{-1}}$. This is essentially smaller than the mass loss rate of the secondary ($\dot{M} \sim 10^{16}\,\mathrm{g\,s^{-1}}$) derived from the observations of the Balmer continuum and the optical/UV emission lines (see e.g. Eracleous & Horne 1996). On this basis they have envisaged a situation in which the major fraction of the plasma inflowing into the Roche lobe of the primary within the orbital plane (so called low-altitude accretion flow) is ejected from the system due to the propeller action, while a small amount of material, which reaches the primary magnetosphere at the bases of the corotational cylinder (so called high-altitude accretion flow)[2], is able to penetrate through the magnetospheric boundary and reach the white dwarf surface. The theoretical analysis of this situation (which has not been performed so far) is the subject of the present paper. I discuss the possible origin of the high-altitude accretion flow (Sect. 2), the efficiency of plasma penetration into the primary magnetosphere through the bases of the corotational cylinder (Sect. 3) and the trajectory of the plasma inside the white dwarf magnetosphere (Sect. 4). My basic conclusion is that the assumption about the accretion nature of the 33 s pulsing component in AE Aqr has no sufficient theoretical grounds and thus, the investigation of alternative mechanisms of the polar caps heating seems to be more fruitful (Sect. 5).

2. The origin of high-altitude accretion flow

In the general case the mass-exchange in a close binary system can be realized due to the stream-fed and/or the wind-fed mass transfer mechanisms. As shown by Ikhsanov (1997) the mass capture rate by the primary from the stellar wind of the normal companion in AE Aqr is limited **to** $\dot{M}_\mathrm{wa} \lesssim 3.3\,10^{12}\,\mathrm{g\,s^{-1}}$. This value is significantly smaller than that required to explain the observed UV/X-ray luminosity of the pulsing component in terms of accretion onto the primary surface. That is why the wind-fed mass transfer mechanism cannot be responsible for the powerful high-altitude accretion flow in AE Aqr.

The effective cross-section of the stream flowing into the Roche lobe of the primary through the L1 point can

[1] Hereafter the distance to AE Aqr is adopted to be 100 pc

[2] According to Patterson (1979) and Eracleous et al. (1994) the rotational axis of the white dwarf in AE Aqr is almost perpendicular to the orbital plane

be limited by the cross-section of the throat at this point, which in the case of AE Aqr is (Ikhsanov 1997)

$$Q = \frac{2\pi c_{\rm s}^2 a^3}{kG(M_1+M_2)} \sim 1.85\times 10^{19} \left(\frac{T}{10^4\,{\rm K}}\right)\ {\rm cm}^2. \qquad (3)$$

Here $c_{\rm s}$ and T are the sound speed and the plasma temperature at the L1 point, a is the orbital separation, M_1 and M_2 are the masses of the primary and the secondary, respectively, and k is a dimensionless constant depending on the mass ratio of the components (for discussion see Meyer & Meyer-Hofmeister 1983). This allows to evaluate the effective radius of the stream at the L1 point[3] as $r_{\rm s} = \sqrt{Q\pi^{-1}} \simeq 2.4\,10^9$ cm.

The stream inside the Roche lobe of the primary follows the ballistic trajectory toward the white dwarf until it interacts with the star magnetic field. The maximum possible expansion of the stream during this part of its trajectory is

$$\Delta r \lesssim t_{\rm ff} c_{\rm s} \simeq 2\,10^9\ R_{11}^{3/2}\ M_{0.8}^{-1/2}\ T_4^{1/2}\,{\rm cm}, \qquad (4)$$

where $t_{\rm ff} = R^{3/2}/\sqrt{2GM_1}$ is the free-fall time, R_{11} is the distance from the white dwarf to the L1 point expressed in units of 10^{11} cm and $T_4 = T/10^4$ K. Hence the altitudes at which the stream flows into the white dwarf magnetosphere can be estimated as

$$|\ \kappa\ | \lesssim \arcsin\left(\frac{r_{\rm s}+\Delta r}{R_{\rm L1}}\right) \simeq 3^{\circ}, \qquad (5)$$

i.e. the material inflowing through the L1 point reaches the white dwarf magnetosphere in a narrow band around the rotational equator of the primary.

The situation could be different if the secondary in AE Aqr essentially overflows its Roche lobe. This assumption, however, contradicts the results of the investigation of gradual variations of optical brightness in the quiescent state (van Paradijs et al. 1989). Furthermore, in this case, the mass transfer rate in the system would be essentially higher than that currently estimated (see Introduction).

An additional possibility to explain the origin of the high-altitude accretion flow is to assume that the temperature of the material surrounding the stream at the L1 point is about of 10^7 K. In this case the value of Δr proves to be comparable to the magnetospheric radius of the white dwarf and, hence, the spherically symmetrical accretion flow onto the primary magnetosphere can be expected. In principle this assumption could be accepted if the mechanism of plasma heating at the L1 point is explained.

3. The efficiency of plasma entry into the magnetosphere of the white dwarf

As shown by Arons & Lea (1976) the mass accretion rate onto the surface of a magnetized compact star is limited by the rate of plasma penetration into the star magnetosphere. The latter depends on the shape of the magnetospheric boundary, the geometry of the accretion flow and the physical parameters of plasma over the boundary. Correspondingly, three modes of plasma penetration into the star magnetic field can be realized: the interchange instabilities, the diffusion, and the reconnection of the magnetic field lines (for discussion see Elsner & Lamb 1984).

Choi & Yi (2000) have distinguished two components of the accretion flow beyond the white dwarf magnetosphere: (i) the accretion stream (the low-altitude component) and (ii) the almost spherically symmetrical accretion flow (the high-altitude component). As shown by Wynn et al. (1997) the stream interacts with the magnetic field of the white dwarf in a local region at low altitudes ($|\ \kappa\ | \lesssim 3°$) mainly at the closest approach to the primary ($r_{\rm ms} \simeq 10^{10}$ cm). The influence of the stream on the large scale field of the white dwarf at higher altitudes (i.e. $|\ \kappa\ | \gg 3^{\circ}$) is small and the dipole approximation for the field of the primary in these regions can be used.

The interaction between the spherically symmetrical accretion flow and the dipole magnetic field of a compact star in the state of propeller has been investigated by Davies et al. (1979) and Davies & Pringle (1981). They have shown that the magnetosphere of the primary in this case is closed[4] and the magnetospheric radius can be evaluated as

$$r_{\rm c} \gtrsim R_{\rm m} = 1.8\,10^{10} \mu_{32}^{4/7} \dot{M}_{15}^{-2/7} M_{0.8}^{-1/7}\,{\rm cm}, \qquad (6)$$

where $\mu_{32} = \mu/10^{32}\,{\rm G\,cm^3}$ and $\dot{M}_{15}$ is the mass accretion rate of the high-altitude component onto the magnetospheric boundary expressed in units of $10^{15}\,{\rm g\,s^{-1}}$.

Under the condition $r_{\rm c} > R_{\rm cor}$, that is just the case of the white dwarf in AE Aqr, the state of the primary is classified as *supersonic propeller* (the linear velocity of the magnetospheric boundary, $v_{\varphi} = 2\pi r_{\rm c}/P_{\rm s}$, exceeds the sound speed in the accretion flow, which is limited by the free-fall velocity, $V_{\rm ff} = \sqrt{2GM_1/r_{\rm c}}$). In this situation the magnetosphere of the star is surrounded by a turbulent atmosphere in which the plasma temperature is of the order of the free-fall temperature $T_{\rm ff} = GMm_{\rm p}/kr_{\rm c}$ (where $m_{\rm p}$ and k are the proton mass and the Boltzmann constant, respectively).

As shown by Davies & Pringle (1981) the rate of plasma penetration through the magnetic field of a compact star, which is in the state of the supersonic propeller, is almost negligible. In the region with $r_{\rm c}\cos\kappa > R_{\rm cor}$ (which in our case corresponds to the magnetic latitudes $|\ \kappa\ | \lesssim 85^{\circ}$) the centrifugal force dominates the gravitational force at the magnetospheric boundary. That is why the plasma entering the magnetosphere in this region is unable to flow along the field lines to the primary surface but is pushed back by the fast rotating magnetosphere. In the region $r_{\rm c}\cos\kappa \lesssim R_{\rm cor}$ (which corresponds

[3] Here I would like to note that the plasma density across the stream at the L1 point is $n_{\rm s} \propto \exp\{-(r/r_{\rm s0})^2\}$.

[4] The shape of the magnetosphere is similar to that derived by Arons & Lea (1976)

to $85^{\circ} \lesssim |\kappa| \lesssim 90^{\circ}$) the centrifugal force is not effective. However, the effective penetration of plasma into the magnetosphere does not occur since the temperature of the plasma over the boundary is $T(r_{\rm c}) \sim T_{\rm ff}$ and hence, the magnetospheric boundary is stable with respect to interchange instabilities (see Arons & Lea 1976; Elsner & Lamb 1977). In this situation the efficiency of plasma penetration into the magnetic field of the primary (due to the magnetic field lines reconnection and/or diffusion) is smaller than 1% (see Ikhsanov 2001 and references therein). Furthermore, the area of the bases of the corotational cylinder in the considered case constitutes about 10% of the total magnetospheric area. That is why the rate of plasma penetration into the white dwarf magnetosphere is at least three orders of magnitude smaller than the initial mass accretion rate in the high-altitude accretion flow. This, however, is too small to explain the luminosity of the 33 s pulsing component.

4. Accretion flow inside the primary magnetosphere

The last item I briefly address in this section is the plasma flow inside the white dwarf magnetosphere. It is well known that the accreting plasma penetrates the magnetosphere across the filed lines forming the magnetopause, which is situated at the boundary and has the thickness $\delta_{\rm m} \ll R_{\rm m}$ (see e.g. Arons & Lea 1976, Ghosh & Lamb 1979 and Elsner & Lamb 1984). Plasma penetrating the magnetosphere flows along the field lines within a relatively narrow channel towards the star surface. Following this way it can reach the star surface if all parts of the channel are situated inside the corotational cylinder (otherwise it will be pushed out from the magnetosphere by the centrifugal force). This condition is always satisfied if the magnetospheric radius of the star is smaller than the corotational radius, i.e. if the star is in the accretor state. But if the star is in the propeller state the realization of this condition is not obvious. The answer depends on whether a magnetic line, which is situated inside the corotational cylinder and connects the star surface with the bases of the corotational cylinder, exists in the magnetosphere.

To investigate this problem I use the dipole approximation for the magnetic field of the primary[5]. A magnetic line of force in this case has the equation

$$r = r_{\rm e} \cos^2 \lambda, \tag{7}$$

where λ is the magnetic latitude and $r_{\rm e}$ is the distance from the line origin to the point of its intersection with the plane of the magnetic equator[6]. I denote the angle between the magnetic and rotational axes of the primary by β and the angle between $\boldsymbol{B}$ and the radius vector by α. The latter can be expressed, according to Alfvén & Fälthammar (1963), as

$$\sin \alpha = \frac{\cos \lambda}{\sqrt{1 + 3 \sin^2 \lambda}}. \tag{8}$$

A situation in which at least one line of force is situated inside the corotational cylinder and connects the star surface with the magnetospheric boundary is shown in Fig. 1. This line has a point of contact with the surface of the corotational cylinder in which the vector $\boldsymbol{B}$ is parallel to the rotational axis of the star, $\boldsymbol{\Omega}$. As it is seen from the figure the following conditions are satisfied in this case

$$\beta = \left(\frac{\pi}{2} - \lambda\right) + \alpha, \tag{9}$$

$$\frac{R_{\rm cor}}{r_{\rm e} \cos^2 \lambda} = \sin \alpha. \tag{10}$$

The value $r_{\rm e}$ for this line can be evaluated taking into account that it reaches the magnetospheric boundary at $\lambda = (\pi/2 - \beta)$. Hence,

$$r_{\rm e} = \frac{r_{\rm m}(\lambda)}{\cos^2 (\pi/2 - \beta)}, \tag{11}$$

where $r_{\rm m}(\lambda)$ is the distance from the white dwarf to the base of the corotational cylinder. According to Arons &

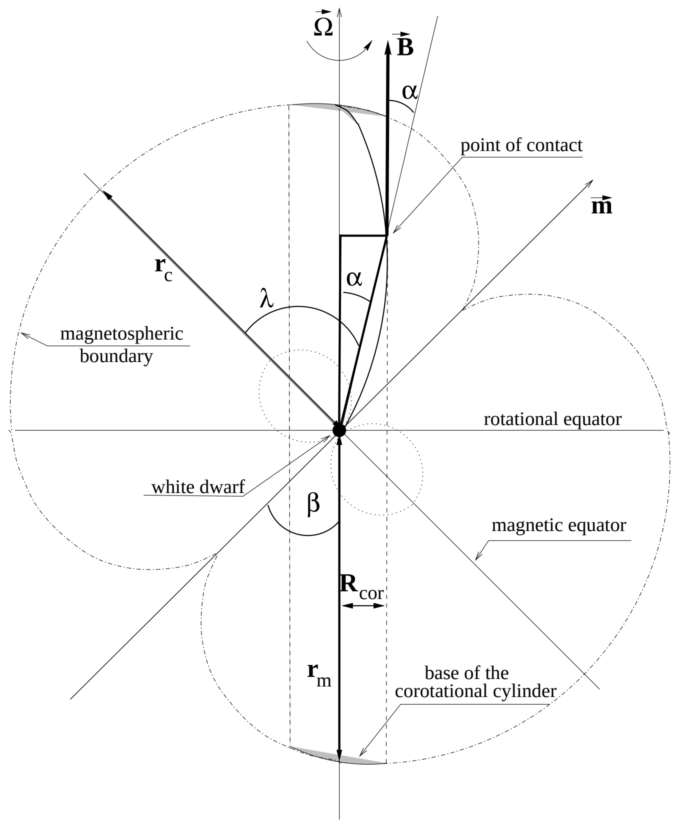

Fig. 1. Schematic description of the magnetosphere of the white dwarf undergoing high-altitude accretion as discussed in the text

[5] This approximation is valid in the region $R_{\rm wd} < r < r_{\rm c}$ (see Arons & Lea 1976).

[6] In the azimuthal direction the equation of the magnetic line of force is $\varphi = $const.

Lea (1976) in the case of spherically symmetric accretion, $r_{\rm m}(\lambda)$ can be approximated as

$$\frac{r_{\rm m}}{r_{\rm c}} \simeq \begin{cases} (\cos\lambda)^{0.2639}, & \text{for} \quad |\,\lambda\,| \lesssim \lambda_0, \\ \\ 0.51 + 0.63\left(1 - \frac{2|\lambda|}{\pi}\right)^{2/3}, & \text{for} \quad |\,\lambda\,| > \lambda_0, \end{cases} \quad (12)$$

where $\lambda_0 \simeq 80^{\circ}$.

Combining Eqs. (7–12) I find that plasma accretion onto the primary surface in the considered case could be realized if the following condition is satisfied

$$\frac{\tan\lambda \sin\lambda}{\sqrt{1+3\sin^2\lambda}} - \frac{r_{\rm c}}{9R_{\rm cor}}(\cos\lambda)^{0.2639} \gtrsim 0. \quad (13)$$

Solving this inequality for λ and putting the result to Eqs. (8) and (9) I find that the accretion process onto the surface of the white dwarf in AE Aqr could be realized[7] if $\beta \lesssim 38^{\circ}$. At the same time, the value of β evaluated by Eracleous et al. (1994) from the investigation of the pulse profiles of the 33 s oscillations is $75^{\circ} \lesssim \beta \lesssim 77^{\circ}$. This indicates that the assumption about the direct accretion of plasma onto the surface of the white dwarf in AE Aqr contradicts the results of optical/UV observations of the system and thus cannot be accepted.

5. Conclusions

One can conclude that the assumption about the direct plasma accretion onto the surface of the white dwarf in AE Aqr cannot be accepted. The theoretical grounds of this conclusion are the following. First, the origin of the high-altitude accretion flow, which moves directly to the bases of the corotational cylinder of the white dwarf with the rate $> 10^{13}\,{\rm g\,s^{-1}}$, in the particular case of AE Aqr, is rather unclear. Second, even if we assume that this accretion flow exists, the efficiency of its penetration into the white dwarf magnetosphere is smaller than 0.1%. Finally, for the established value of the angle between the rotational and magnetic axes of the white dwarf in AE Aqr, the material penetrating the magnetosphere through the bases of the corotational cylinder could never reach the star surface flowing along the magnetic field lines.

From the observational point of view the assumption about the accretion onto the surface of the white dwarf in AE Aqr also faces a number of serious problems. In particular, the temperature of the plasma in the polar caps of the white dwarf in AE Aqr ($T \simeq 26000\,{\rm K}$) derived by Eracleous et al. (1994) is significantly smaller than the surface temperature in the magnetic pole regions of accreting white dwarfs (typically $T \sim 10^8\,{\rm K}$, Eracleous et al. 1991). Furthermore, the X-ray spectrum of AE Aqr is soft and essentially differs from the hard X-ray spectra of all intermediate polars as well as from those of almost all accretion powered close binaries (Clayton & Osborne 1995). On the other hand, due to the power law spectrum with $\alpha \approx -2$ and the ratio of the X-ray luminosity to the spindown luminosity $L_{\rm x}/L_{\rm sd} \sim 10^{-3}$, the X-ray emission of AE Aqr is rather similar to the X-rays detected from spin-powered pulsars (Becker & Trümper 1997). This resemblance indicates that the energy release in the magnetosphere of the white dwarf in AE Aqr and the magnetospheres of spin-powered pulsars may have a common nature and, if so, the assumption about the accretion onto the white dwarf surface proves not to be necessary.

[7] The corotational radius and the equatorial magnetospheric radius of the white dwarf are taken as $R_{\rm cor} = 1.5\,10^9$ cm and $r_{\rm c} = 1.8\,10^{10}$ cm, respectively (see above)

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